Published online March 8, 2006

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WEPP Simulation of Observed Winter Runoff and Erosion in the U.S. Pacific Northwest

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ABSTRACT

The Palouse area of the Northwestern Wheat and Range Region suffers high erosion throughout the winter season. The excessive soil loss is a result of a combination of winter precipitation, intermittent freezing and thawing of soils, steep land slopes, and improper management practices. Soil strength is typically decreased by the cyclic freeze and thaw, particularly during the period of thawing. When precipitation occurs during these freeze–thaw cycles, soil is easily detached and moved downslope. This study was aimed at improving the knowledge of winter hydrology and erosion in the Pacific Northwest (PNW) through combined field experimentation and mathematical modeling. Surface runoff and sediment were collected for three paired field plots under conventional tillage and no-till, respectively. Additionally, transient soil moisture and temperature at various depths were continuously monitored for two selected plots. These data were used to assess the suitability and performance of the USDA's Water Erosion Prediction Project (WEPP), a physically based erosion model, under the PNW winter conditions. Field observations revealed that minimal erosion was generated on the no-till plots, whereas erosion from the conventionally tilled plots largely exceeded the tolerable rates recommended by the Natural Resources Conservation Service. The WEPP model could reasonably reproduce certain winter processes (e.g., snow and thaw depths and runoff) after code modification and parameter adjustment. Yet it is not able to represent all the complicated processes of winter erosion as observed in the field. Continued field and laboratory investigation of dynamic winter runoff and erosion mechanisms are necessary so that these processes can be properly represented by physically based erosion models.

Soil erosion rates in the Palouse and Nez Perce Prairies of the Northwestern Wheat and Range Region (Austin, 1981) vary among the seasons, with as high as 85% of soil loss occurring during winter (McCool et al., 1976; Zuzel et al., 1982; McCool, 1990). This excessive soil loss is a result of a combination of winter precipitation, intermittent freezing and thawing of soils, steep land slopes, and management practices that often leave the soil pulverized and unprotected during the rainy season (Papendick et al., 1983; McCool et al., 1987). Summer fallow followed by winter wheat (*Triticum aestivum* L.), traditionally a major cropping system in the Palouse Region, has long been a significant contributor to water erosion (Papendick et al., 1995). When fields are summer fallowed for a year under conventional tillage, the fallowed land is clean tilled to control weeds and store seed-zone moisture for the next year's crop. Without soil surface cover, the surface layer is highly prone to water erosion when it becomes saturated during the winter precipitation season. In the higher precipitation zone of the Palouse, water is generally adequate for annual cropping, and summer fallow has become less frequently used. However, a small percentage of producers still use the practice on an occasional basis (McCool et al., 2001).

The unique winter climatic conditions of the inland PNW typified by frequent freeze and thaw cycles further aggravates the already elevated vulnerability to erosion caused by conventional farming practices. Most water erosion in the Palouse region is related to rain on frozen or thawing soils and is often exacerbated by the warm, moist Pacific air masses that cause precipitation combined with rapid thaw (Yoo and Molnau, 1982; Zuzel et al., 1982). During freezing, water moves from deeper soil layers and concentrates in the frozen zone. Frost heave and expansion of soil pores frequently result. When a warming trend occurs and the soil begins to thaw, the expanded surface layers are at a high water content and can be easily detached. When a rainfall event occurs under these conditions, there is essentially no place for the water to go but down the slope, increasing the likelihood of soil erosion.

The rate and depth of soil freezing is largely determined by tillage type, surface residue, water content, and water infiltration rate (McCool et al., 2000). Vomocil et al. (1984) discovered that surface residues help reduce soil freezing, but the extent of the effects of different types of residue on frost depth has not been studied thoroughly. Residue also reduces relative heat loss at night, air movement near the soil surface, and freezing depth (McCool et al., 2000). Field management also has a profound affect on the spatial variation of frost depth. Veseth et al. (1986) observed that rough tillage leads to a nonuniform frost depth, as compared with standing stubble or a smooth tilled soil surface. A study conducted near Pendleton, OR revealed a deeper frost depth (~15 mm) under a conventionally tilled field and a much shallower frost depth (<5 mm) under a no-till field with heavy residue (Greenwalt et al., 1983). Additionally, McCool et al. (2000) found that crop management had a major effect on both runoff and soil loss. The effect was greater on soil loss than on runoff for all observed conditions, and the presence of a frost layer reduced the effect of crop management on runoff more than on soil loss.

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Published in Vadose Zone Journal 5:261–272 (2006).
Special Section: From Field- to Landscape-Scale Vadose Zone Processes
doi:10.2136/vzj2005.0055
© Soil Science Society of America
677 S. Segoe Rd., Madison, WI 53711 USA

Abbreviations: CT, conventionally tilled [plot]; ET, evapotranspiration; NT, no-till [plot]; OFE, overland flow element; PCFS, Palouse Conservation Field Station; PNW, Pacific Northwest; WEPP, Water Erosion Prediction Project.

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The processes of rill generation and changes in soil strength during all phases of freezing and thawing have not been well understood. The Palouse region can undergo more than 120 freeze–thaw cycles during a normal winter season (Hershfield, 1974). Soil freeze–thaw processes affect soil cohesive strength and increase soil erodibility (Formanek et al., 1984). During the thawing process, soil ice water melts and aggregates of the soil particles cannot reabsorb all of the available water, often leading to severe saturation at the surface and causing the soil to be weaker after thawing than before freezing (Formanek et al., 1984). Severe erosion from such unconsolidated soil may result even from low intensity rainfall and saturation excess runoff (Van Klaveren and McCool, 1998). Formanek et al. (1984) performed a series of shear strength experiments in both the laboratory and field with a fall-cone device. They found that, for the Palouse silt loam soil under test, both the shear strength and erosion resistance approaches some minimum value during thawing. They also pointed out that both the rate of the freezing–thawing cycles and the timing of any precipitation event interactively affect erosion in a dynamic manner.

A comprehensive study aimed at improving knowledge of winter hydrology and erosion in the PNW was initiated under the funding support of USDA CSREES National Research Initiative program in 2002. The study consists of extensive laboratory and field investigations as well as the incorporation of the experimental results into a mathematical water erosion model, more specifically, the USDA's Water Erosion Prediction Project (WEPP) model (Nearing et al., 1989; Laflen et al., 1991). As an integral component of this study, long-term erosion research plots were instrumented in the winter season of 2003–2004 at the Palouse Conservation Field Station (PCFS) near Pullman, WA. A series of erosion experiments and observational plots at the PCFS were established in the late 1970s to assess the winter erosion mechanics in the PNW. A 13-yr erosion study was conducted starting in the fall of 1978. This field investigation evaluated surface runoff and erosion as impacted by various tillage and residue management practices. In the current research, the focus is on two representative tillage treatments: conventionally tilled "black fallow" and typical no-till with direct-seeded annual winter wheat (cv. Madsen). In addition to winter runoff and erosion, soil water and temperature profiles were continuously monitored to generate information for elucidating the physical processes of soil water and heat movement, which affects surface runoff and water erosion. The main purposes of our paper are to report the field experimental results from the 2003–2004 winter season at the PCFS and to use this field data to assess the adequacy and performance of WEPP for water erosion prediction under the physical conditions of the inland PNW.

MATERIALS AND METHODS

Experimental Site

The PCFS, where the experimental plots for this study were established, is located 3 km northwest of Pullman, WA (46°45.4′ N, 117°11.3′ W) at an elevation of 762 m above mean sea level. Soil covering the PCFS plots is Palouse silt loam (fine silty, mixed Mesic-Pachic, Ultic, Haploxeroll), which originated from ancient windblown loess (USDA Soil Conservation Service, 1980). The length of the experimental plots was standardized during the winter season of 1987–1988 at approximately 24 m to allow for adequate collection of runoff and sediment (McCool et al., 2001). Among these plots, six were chosen for this study. These plots were 3.7 m wide, on south-facing slopes of 17 (Plots 5 and 6), 23 (Plots 1 and 2), and 24% (Plots 3 and 4), respectively. The plots were V-shaped on both ends to provide resistance to boarder failure at the top and to ensure a collection gradient at the bottom. Additionally, the plots were bordered with a 200-mm galvanized sheet metal forced approximately 100 mm into soil. The six plots were divided into three paired plots with treatments of no-till (NT) annual winter wheat (Plots 2, 4, and 5) and conventionally tilled (CT) black fallow (Plots 1, 3, and 6). The adjacent distance between pairs of the CT and NT plots was roughly 80 m. The average area of plot coverage was 86.3 m^2.

In the 3 yr before 2003 (2000–2002), a typical spring and fall grain crop (spring barley [*Hordeum vulgare* L.] or wheat, winter wheat) rotation, with standard no-till practices was applied to the experimental plots. Since the start of our field experiment in 2003, tillage and planting procedures for these CT and NT experimental plots have been slightly different from the standard cross-slope practices on typical farms in the Palouse region. Although a separate study on rill erosion under CT conducted during the 2000–2001 winter season encompassed Plots 1 and 2, the impact of this previous study was regarded as diminishing with time.

For the three NT plots, a spring barley (cv. Baronesse) crop was planted in April of 2003 over winter wheat residue of 6.3 t ha^{-1} on the average. The spring barley was harvested in early September, and winter wheat was subsequently planted upslope with a USDA V cross-slot drill. For the three CT plots, initial preparation of the black fallow condition in late summer of 2003 included surface irrigation and residue burning to remove large amounts of aboveground biomass. Tillage was then performed three times in early September by roto-till with an overall depth ranging from 15 to 18 cm. Continuously tilled black fallow with no winter crop was chosen as the "worst case" scenario of soil erosion in the PNW. Continuously tilled soils have very low biomass accumulation and the surface soil is pulverized with little or no residue. No-till (or direct seed), in contrast, has proved to be among the most effective conservation practices in reducing erosion and has been widely recognized as the general trend in sustainable agriculture.

The Palouse soil was sampled at three locations, two on the CT Plot 1 and one on the NT Plot 2. At each location, soil coring to the 1-m depth was performed in sequential intervals with a Giddings device. Undisturbed samples were used to measure saturated hydraulic conductivity (K) with the constant-head method (Klute and Dirksen, 1986) and dry bulk density with the core method (Blake and Hartge, 1986). Both undisturbed and disturbed samples were used to determine organic matter by dry combustion (Sheldrick, 1984), and to analyze particle size distribution by sieving and static light scattering after removing carbonates and organic matter (Kunze and Dixon, 1986). The laboratory-determined soil properties for the CT Plot 1 were then averaged for the selected intervals as inputs to subsequent WEPP modeling (Table 1).

Field Instrumentation and Monitoring

Each of the six plots was connected at the bottom to a 2.27-m^3 (600-gallon) sediment delivery tank via a 5-cm-diameter galvanized pipe for runoff and sediment yield sampling.

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Table 1. Physical properties of Palouse silt loam measured for the CT Plot 1.

Layer	Depth	K†	OM	ρ_b	Sand	Clay
	m	10^{-5} m s^{-1}	%	g cm^{-3}	%	
1	0–0.1	3.94‡ (1.73)§	4.25 (0.198)	1.32 (0.09)	19.97 (0.03)	13.54 (0.02)
2	0.1–0.2	1.48 (0.25)	3.51 (0.417)	1.32 (0.08)	14.59 (0.01)	16.06 (0.002)
3	0.2–0.4	1.15 (0.16)	3.18 (0.344)	1.38 (0.08)	24.21 (0.02)	13.12 (0.02)
4	0.4–0.6	2.12 (0.16)	3.55 (0.185)	1.47 (0.16)	39.03 (0.02)	8.80 (0.008)
5	0.6–0.8	4.44 (0.28)	3.28 (0.308)	1.41 (0.03)	19.36 (0.02)	13.58 (0.02)
6	0.8–1.0	1.29 (0.14)	2.73 (0.741)	1.57 (0.06)	18.21 (0.01)	12.72 (0.01)

† K, saturated hydraulic conductivity; OM, organic matter content; ρ_b, soil dry bulk density.
‡ The K value for the surface layer was somewhat higher than those reported for the Palouse silt loam in previous studies, e.g., K as arithmetic or geometric means ranging 3.6×10^{-6} to 2.7×10^{-5} m s^{-1} measured using undisturbed core samples taken from conventionally-tilled fields (Fuentes et al., 2004), K as geometric means ranging 8.8×10^{-7}–5.9×10^{-5} m s^{-1} measured using a Guelph Permeameter in crop fields under different tillage treatments (Kenny, 1990), and K estimated from runoff plot studies ranging 1.9×10^{-6}–1.2×10^{-5} m s^{-1} (Elliot et al., 1989).
§ Numbers in parentheses are one standard deviation calculated from 3 to 12 soil samples.

Moreover, three frost tubes (plastic fluorescein dye tubes that change from blue to clear as a result of freezing) extending to the depth of 1.2 m were installed on each plot, and frost as well as thaw depths were recorded manually whenever frost was expected to be present and persistent. Plots 1 and 2 were intensively instrumented for collecting climatological and soil water and temperature data. Additional weather data were available from the NOAA Pullman 2NW weather station located 0.4 km to the east of the experimental plots.

Instrumentation for field observation of runoff and erosion was installed on 17 Nov. 2003, for the 2003–2004 winter season. The runoff and erosion samples were collected on an event basis and were separated into frozen, thawed, and unfrozen events by frost tube readings and soil temperature profile data. Total runoff volume was determined by measuring multiple depths in the calibrated collection tank along with sonic depth sensors installed for estimating the runoff hydrograph. Before extracting runoff samples, sediment within the tank was resuspended with the jet on a large 5-hp pump. Subsequently, a 150- to 190-L (40–50 gallon) portion was transferred, with the pump, into a sampling container. The sediments within the sampling container were again resuspended for approximately 5 min. Two, 1-L samples were then taken for analysis. Sediment concentration was determined gravimetrically after oven drying of the complete sample.

Monitoring of the soil moisture and temperature profile during the winter season was started on 16 Dec. 2003 and was accomplished using several types of electronic sensors. Thermocouples and ECHO probes (Model ECHO-20, Decagon Devices Inc., Pullman, WA) were used to monitor soil temperature and moisture, respectively, at different depths (surface, 2, 4, 8, 16, 32, 64, and 100 cm) for their ease of installation and relatively low cost. The ECHO probes were individually calibrated in the laboratory with field soil. In addition, heat dissipation sensors (Model 229L, Campbell Scientific, Logan, UT) were used for matric potential estimation at each of these depths.

An automatic weather station was installed directly between Plots 1 and 2, at the midway point of the experimental hillslope. Two anemometers were used to measure the wind speed, one at the 3-m height and another at the 0.25-m height (for canopy wind speed above the standing winter wheat stubble over the NT Plot 2). To measure the net radiation and relative humidity we installed net radiometers (Model Q7.6.1-L, Radiation and Energy Balance Systems, Bellevue, WA) and a Vaisala Temperature and Relative Humidity Probe (CS500-L, Campbell Scientific) at 1-m height above the ground. All electronic data were collected at 15-min intervals on a datalogger (Model CR-10X, Campbell Scientific). Multiple frost tubes were placed into the soil profile on the outside corners of the experimental plots and directly next to the shallow surface electronic instruments.

WEPP Simulation

Model Description

WEPP, a computer-implemented, physically based model, was initially developed in the late 1980s and has been continually improved by the USDA-ARS (Laflen et al., 1997). WEPP is based on the fundamentals of hydrology, erosion mechanics, plant growth, and open channel hydraulics (Flanagan et al., 1995). WEPP has both a hillslope and a watershed version and can be used to model spatial and temporal distributions of net soil loss and sediment deposition along a hillslope or across a watershed on an event or a continuous basis (Flanagan and Nearing, 1995). A hillslope may comprise one or more overland flow elements (OFE), with each OFE representing a region of unique soil, plant, and cultural practice conditions. An OFE can be further discretized in the vertical direction into multiple soil layers of distinct properties.

Detailed description of the WEPP model and summary of important model components and functions can be found in the *WEPP User Summary* (Flanagan and Livingston, 1995) and *WEPP Technical Documentation* (Flanagan and Nearing, 1995). Briefly, WEPP allows the use of a daily climate input for continuous simulation, or break-point climate input for event-based simulation. For continuous simulation, when observed climatic data are not available, CLIGEN, a random climate generator embedded in WEPP, can be used to generate daily data for long-term or single-storm simulations based on historical records. CLIGEN contains daily, hourly, and 15-min historical data for more than 2600 stations across the USA processed by the National Climatic Data Center, Asheville, NC (Nicks et al., 1995).

In the hydrology component of WEPP, infiltration is estimated using a modified Green–Ampt equation, where redistribution is determined following a "capacity limiting" approach. Potential evapotranspiration (ET) is determined following the Penman equation (Penman, 1963). and actual ET is estimated based on the approach of Ritchie (1972). Surface runoff is modeled with an approximation of the kinematic-wave equation, a simplified form of the St. Venant model.

WEPP partitions soil erosion into two parts: interrill erosion and rill erosion. The former contains soil detached by raindrop impact transported by sheet flow and delivered to rill channels. The latter contains soil detached and transported, or deposited, in rills due to concentrated flow.

For this study, the hillslope version of WEPP was used with a single OFE considering the relatively simple hillslope configuration of the experimental plots and vegetation and soil conditions. The event-based simulation mode was used to better represent the precipitation input characteristics. WEPP simulation was made only for Plot 1 under CT treatment because most of the runoff and erosion events occurred on the CT plots,

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and also because Plot 1 was the only CT plot extensively instrumented for both surface runoff and erosion, as well as soil moisture and temperature.

WEPP Inputs

The hillslope version of WEPP requires four input files: climate, soil, slope, and management. The climate input file includes daily precipitation (in break-point form), air temperature, solar radiation, wind speed and direction, and dew-point temperature. The precipitation data were taken from the NOAA 2NW Pullman weather station records by reading the Belfort rain gage chart. The daily maximum and minimum air temperature data were downloaded from the National Climatic Data Center (NCDC, 2004). The remaining climatic parameters were then generated using CLIGEN, which reserves the values of precipitation and temperature observation data. The reason to use the precipitation and air temperature data from the NOAA weather station instead of the newly installed automatic weather station was twofold. First, there existed discrepancies between the precipitation amounts for several major events recorded by the two stations (although the temperature data were agreeable). Since the NOAA station is properly equipped with multiple devices (tipping bucket and weighing rain gages with wind shields and an additional snow collection device) for precipitation measurements, we considered these precipitation records more reliable. Second, at the NOAA station, the rain and snow events are manually separated on a daily basis, and the distinction between event types is important for elucidating the mechanisms of winter runoff and erosion generation.

Soil input includes soil hydraulic conductivity at saturation and soil erodibility parameters (rill and interrill erodibility and critical shear) for the top soil layer and textural information and other physical properties (percentage clay, sand, and organic matter) for each discretized layer. For the CT Plot 1, the soil profile extending from the surface to the 1-m depth was discretized into six layers with a 0.1-m increment for the first two layers in accord with the primary and secondary tillage layers, and a 0.2-m increment for the remaining four layers. Soil textural and hydraulic properties were taken directly from the laboratory measurements (Table 1). Two soil erodibility parameters for the Palouse silt loam, the rill erodibility (K_r) and critical shear (τ_c), were from WEPP technical documents (Elliot et al., 1989). The third parameter, the interrill erodibility (K_i), was from a more recent reference by Fangmeier et al. (2005). In addition to the soil properties, most other parameters (e.g., climate, slope, and management) were also acquired through laboratory and field measurements while the remaining were from the literature.

Slope input includes aspect, representative slope width and length, and shape of the hillslope as represented by paired data of relative distance from the top of an OFE and corresponding slope steepness for up to 20 slope points. For the PCFS plots, elevations at key points along the slope were measured using a laser level, and the slope steepness was calculated accordingly. For Plot 1, a total of 11 paired relative distance and slope steepness values were included to describe the shape of the hillslope.

Management input contains information for plant growth, initial field condition, and yearly management operations. The crop-specific physiological data for winter wheat were taken directly from the *WEPP User Summary* (Flanagan and Livingston, 1995), and information about initial conditions (e.g., initial ridge height and snow and frost depths) and yearly tillage and residue management practices (e.g., time of planting, tillage, and harvest) were measured and monitored in the field. Important soil, slope, and management input parameters for WEPP simulation are included in Table 2.

Table 2. Important soil, slope, and cultural practice parameters used in the WEPP simulations.

Parameter	Value
Hillslope configuration	
Number of overland flow elements (OFEs)	1
Profile aspect (clockwise from north), °	182
Representative profile width, m	3.7
Number of slope points on the OFE	11
Length of the OFE, m	24.7
Present soil properties	
Texture	silt loam†
Number of soil layers	6
Albedo	0.08
Initial saturation of soil porosity, m m^{-1}	0.9
Baseline interrill erodibility, kg s m^{-4}	4.95×10^6
Baseline rill erodibility, s m^{-1}	6.55×10^{-3}
Baseline critical shear, N m^{-2}	0.74
Effective hydraulic conductivity of surface soil, m s^{-1}‡	3.94×10^{-5}
Cultural practice§	
Land use	cropland
Plant name	spring wheat, winter wheat
Canopy cover coefficient	5.2
Base daily air temperature, °C	4
Growing degree days to emergence, °C	60
Height of post harvest standing residue; cutting height, m	0.152
Plant stem diameter at maturity, m	6.4×10^{-3}
Radiation extinction coefficient	0.65
Standing to flat residue adjustment factor (wind, snow)	0.99
Max. Darcy Weisbach friction factor for living plant	3
Growing degree days for growing season, °C	1700
Harvest index	0.42
Max. canopy height, m	0.91
Decomposition constant to calculate mass change of both root biomass and aboveground biomass	8.5×10^{-3}
Optimal temperature for plant growth, °C	15
Plant specific drought tolerance	0.25
In row plant spacing, m	0.005
Max. root depth, m	0.3
Root/shoot ratio	0.25
Period of senescence occurs, d	14
Max. leaf area index	5
Rill and interrill tillage intensity for nonfragile crops	0.1
Number of rows of tillage implement	20
Ridge height value after tillage, m	2.54×10^{-2}
Ridge interval, m	0.2
Random roughness value after tillage, m	0.12
Fraction of surface area disturbed	0.85
Bulk density after last tillage, 1.5×10^3 kg m^{-3}	1.15
Initial canopy cover¶	0
Days since last tillage	105
Days since last harvest	119
Initial frost depth, m	0.12
Initial residue cropping system	fallow
Cumulative rainfall since last tillage, mm	101.6
Initial ridge height after last tillage, m	2.54×10^{-2}
Initial ridge roughness after last tillage, m	0.01
Initial snow depth, m	2.54×10^{-2}
Depth of primary tillage layer, m	0.2

† Texture information includes sand and clay percentage which is shown in Table 1.
‡ The effective saturated hydraulic conductivity, with an initial value of 3.94×10^{-5} m s^{-1} from the laboratory measurements, is internally adjusted for field conditions such as worm holes and tillage and for winter conditions.
§ All the plant physiological parameters were from the WEPP User Summary (Flanagan and Livingston, 1995). For spring wheat and winter wheat, these parameters are the same.
¶ The initial conditions correspond to the field conditions at the beginning of 2002.

WEPP Runs

WEPP simulation was made for a period of 3 yr (2002–2004) by considering that antecedent field conditions, which were largely affected by previous tillage practices and crop rota-

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Table 3. WEPP-predicted surface runoff (R), soil evaporation (E_s), deep percolation (D_p), and erosion in comparison with field observation during Nov 17, 2003–Mar 6, 2004. In all runs, subsurface lateral flow was zero.

WEPP run	K_f, τ_c†	Precip.	R	E_s‡	D_p	Erosion
		mm				t ha^{-1}
1	$K_f = 0.1K$ $\tau_c = 0.74$ Pa	270.6	0.0	141.1	75.0	0.0
2	$K_f = 0.0001K$ $\tau_c = 0.74$ Pa	270.6	37.2	116.5	54.1	8.5
3	$K_f = 0.00005K$ $\tau_c = 0.74$ Pa	270.6	62.7	103.5	41.4	11.6
4	$K_f = 0.00005K$ $\tau_c = 0.1$ Pa	270.6	62.7	103.5	41.4	34.6
Observed	–	270.6	66.7	–	–	69.7

† K_f is the minimum saturated hydraulic conductivity under winter (freezing soil) conditions, taken as a fraction (default value of 0.1) of K, the effective saturated hydraulic conductivity under nonwinter conditions, in the original WEPP code. τ_c is soil critical shear stress.
‡ No plant transpiration was predicted since the field was under fallow.

tions, may have substantially impacted runoff and erosion during the field monitoring period. Four WEPP runs (Table 3) were made. In the first run, the original WEPP code (v2004.7) was used, together with all the major input parameters as listed in Table 2. In the second and third runs, changes were made to the winter subroutines of WEPP such that saturated hydraulic conductivity (K) would be reduced by 10 000 and 20 000 times, respectively, instead of 10 times, as in the original code, when the winter routine is invoked. The reductions in K were based on the findings of McCauley et al. (2002) that K can be reduced by four to five orders of magnitude in frozen soils. In the fourth run, the critical shear stress, τ_c, was reduced from the default value of 0.74 to 0.1 Pa following Elliot et al. (1989) in which a wide range of linearly fitted τ_c values (−0.7–2.1 Pa with a mean of 0.74 Pa) was reported for a number of the tests on the Palouse silt loam.

RESULTS AND DISCUSSION

Field-Observed Winter Runoff and Erosion

In total, 14 runoff and erosion events were observed starting 17 Nov. 2003 and ending 6 Mar. 2004. The CT plots (Plots 1, 3, and 6) generated different amounts of runoff and sediment for every event (Fig. 1). Plot 1 generated runoff and erosion in all events, but Plots 3 and 6 did not generate significant runoff and sediment for the first four events. This outcome may be attributed to the naturally existing spatial variation, or it had not been

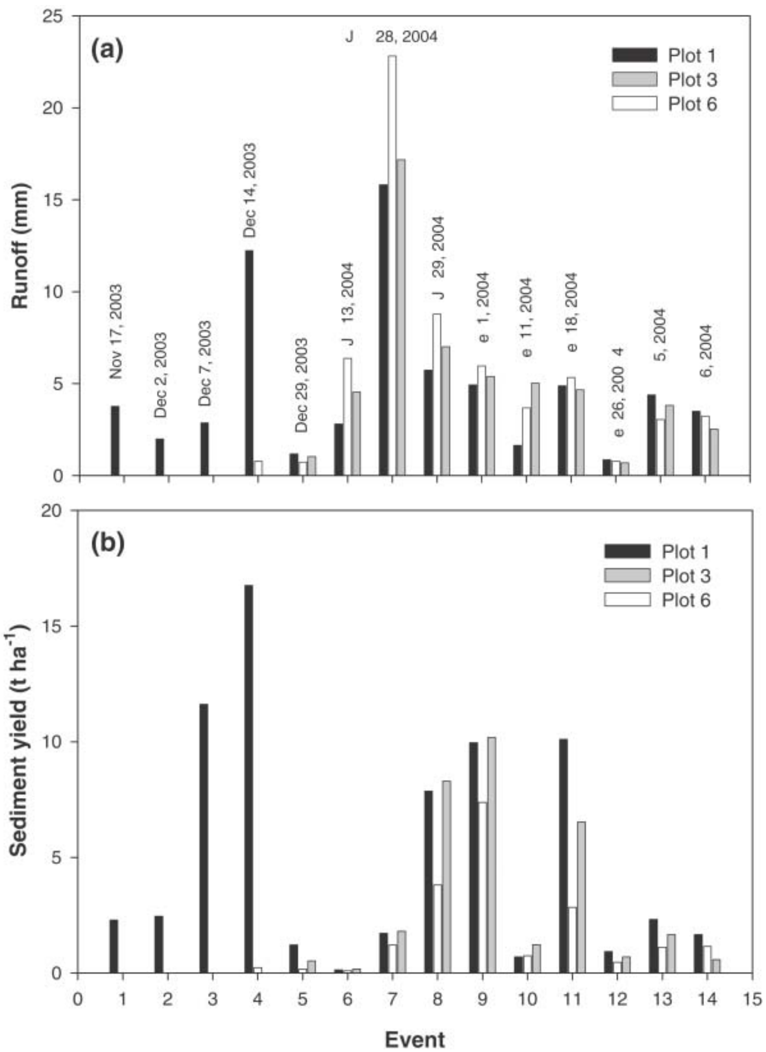

Fig. 1. Observed (a) runoff and (b) erosion from conventional tillage (CT) plots.

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long enough to diminish the impact of the previous study. For every subsequent event, however, runoff and erosion occurred on all three plots. Total observed runoff and sediment for Plots 1, 3, and 6 were 66.7 mm and 69.7 t ha^{-1}, 51.9 mm and 31.7 t ha^{-1}, and 61.5 mm and 19.2 t ha^{-1}, much higher than the tolerable rates of

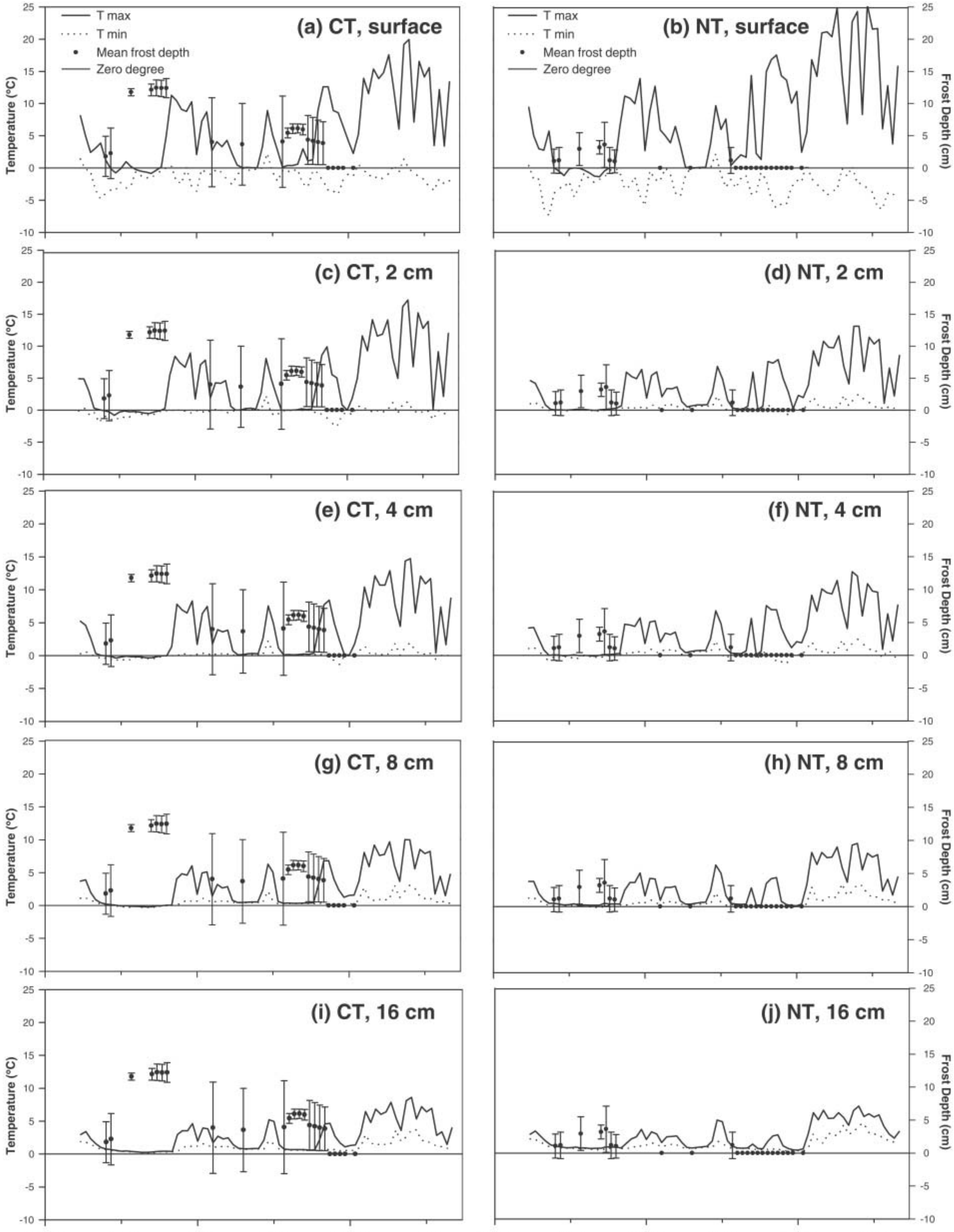

Fig. 2. Soil temperature profile and frost depths under conventional tillage (CT Plot 1, in panels a, c, e, g, and i) and no-till winter wheat (NT Plot 2, in panels b, d, f, h, and j) for different depths.

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5.0 to 12.0 t ha^{-1} recommended by the USDA-NRCS (USDA, 1981). On the other hand, runoff and erosion rarely occurred on the NT plots—Plots 2 (0.3 mm and 0.2 t ha^{-1}) and 5 (0.5 mm and 0.001 t ha^{-1}) each had only one event, and Plot 4 had no events.

Daily maximum and minimum soil temperatures at different depths, aggregated from 15-min records, are shown in Fig. 2. Increased dampening to surface temperature was evident with increasing depths. The soil temperature profile allowed for separation of runoff events into the categories of frozen, thawing, and unfrozen. Also shown in Fig. 2 are the mean frost depths with one standard deviation above and below the mean values. During the 2003–2004 season one major frost event occurred, with the freezing front reaching 11 cm below surface. In general, the frost tubes responded to soil freezing in a delayed manner. Spatial variability was a predominant characteristic, yet spatial variation in measured frost depths decreased with time during the prolonged frost. In general, frost tube readings appeared closely related to the maximum and minimum soil temperatures measured by thermocouples near the freezing front. When rapid freezing and thawing occurred, the readings of frost tubes tended to become unstable, as shown in the measurements from 16 Jan. to 1 Feb. 2004 (Fig. 2).

Soil moisture data measured by the ECHO probes and from soil core samples are shown in Fig. 3. Undisturbed soil sample data revealed that the ECHO probes tended to under-measure the volumetric water content in the shallow soil zone. There might be multiple reasons for the lower readings by the ECHO probes. First, instrument contact with the surrounding soil is paramount to a correct soil moisture content reading. However, after installation, this contact might be drastically affected by the seasonal soil structure changes, particularly in the shallow zone, as caused by the freeze–thaw cycles and moisture content changes. Second, the diurnal temperature fluctuations, evident in the first third of Fig. 3 (4–15 Feb. 2004), might influence the ECHO probe measurements. Typically, if the soil temperatures around a probe reach freezing, the probe would not be able to detect ice soil water. Nonetheless, an unfrozen portion of the probe would still be able to detect the liquid soil water, but this measurement is unreliable and not representative of the entire length of the probe. Although a temperature correction equation provided by the manufacture of the ECHO probes could have been used when the temperature measurements made simultaneously next to the probes were available, we have found this temperature correction equation incorrect from current laboratory tests (R.H. Cuenca, Dep. Bioeng., Oregon State Univ., personal communication, 2005). The ECHO probe measurements for deeper soil zone (at 32- and 64-cm depths, Fig. 3) may be more reliable because the lower soil layers tended to be less responsive

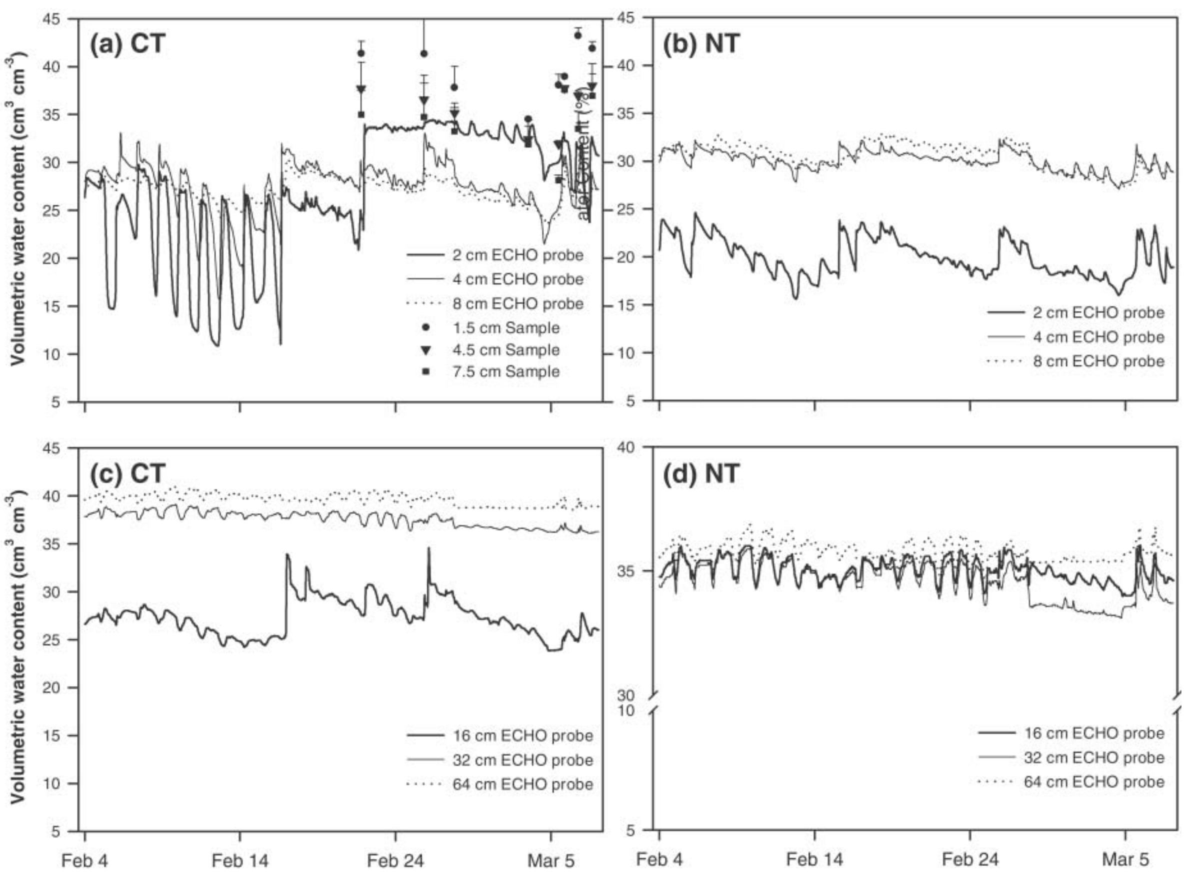

Fig. 3. Volumetric soil water content recorded by ECHO probes and undisturbed soil core sampling under conventional tillage (CT, in panels a and c) and no-till winter wheat (NT, in panels b and d) for different depths.

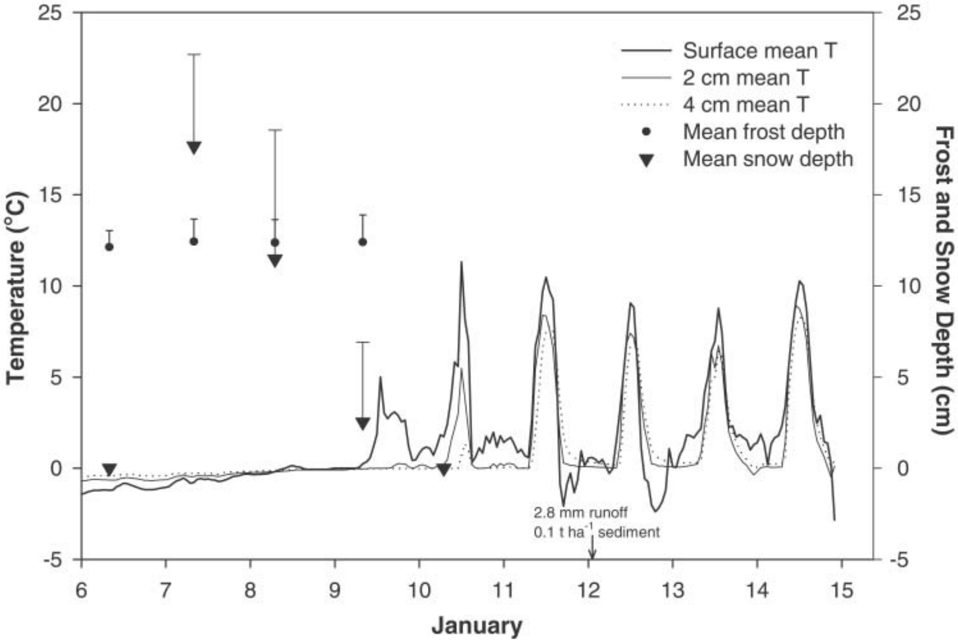

Fig. 4. A runoff event due to soil thawing and snowmelt on 12 Jan. 2004.

to the dynamic temperature fluctuations and soil structure changes.

Runoff and erosion may result from soil thawing and snowmelt. Figure 4 shows a typical event of this type that ended on 12 Jan. 2004. This event produced 2.8 mm of runoff and 0.1 t ha^{-1} of sediment. Detailed event monitoring revealed that there was no precipitation; this event was mainly caused by soil thawing and snowmelt on the black fallow Plot 1. Due to the naturally occurring soil spatial variability, there exists spatial variability in the frost depth and frost lens, which in turn affects infiltration capacity and runoff generation. Observation during this event revealed the lower portion of the plot to be at saturation and wetter than the upper portion, suggesting saturation excess as the possible mechanism. Further, before the completion of the event, a night-time freeze event occurred. This freeze "pulled" additional water to the surface layer where it was already near saturation, creating a condition ripe for this event. Such night-time freeze and day-time thaw occurred frequently throughout the winter season (Fig. 2 and 4), weakening the soil at the surface.

Figure 5 illustrates two events that are in close succession at the end of January 2004. With soil surface

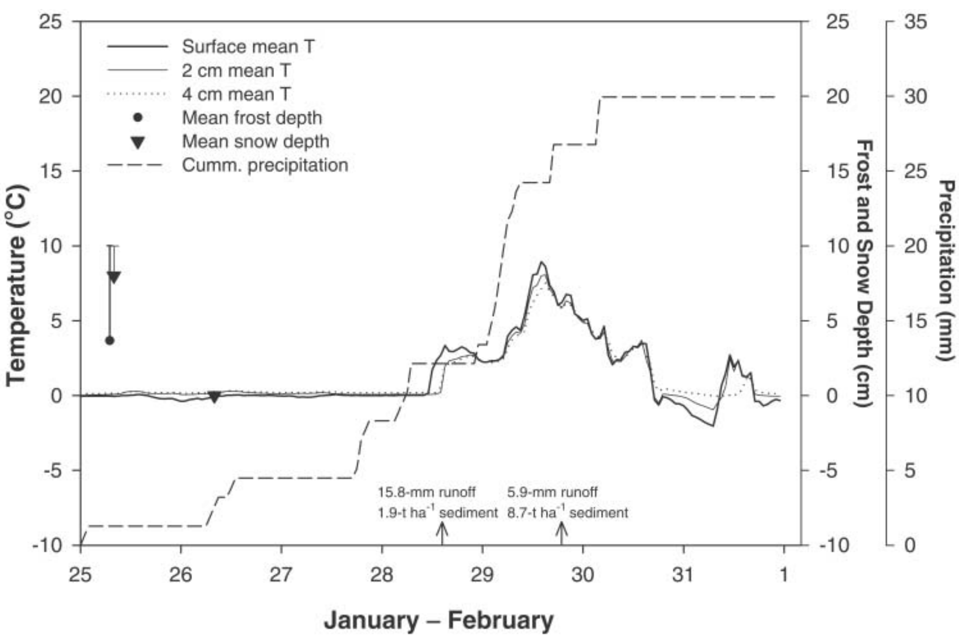

Fig. 5. Successive runoff events caused by rain on snow followed by rain only on 28–29 Jan. 2004.

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temperatures remaining near 0°C, a precipitation-driven snowmelt started to occur on 25 January. As rainfall increased with time over the frozen soil, the first event was recorded, which produced more runoff (15.8 mm) and less sediment (1.9 t ha^{-1}). The low sediment yield in this event possibly indicated relatively lower rill and interrill erodibilities, as well as a higher critical shear of the soil undergoing the initial stage of thawing. With the soil already at saturation, an additional, higher intensity precipitation event began. This second event resulted in less runoff (6.0 mm) but greater erosion (8.7 t ha^{-1}). The elevated erosion likely implied increased rill and interrill erodibilities and decreased critical shear stress. Kok and McCool (1990) observed that soil weakened rapidly during thawing, and that when precipitation immediately followed surface thawing, the soil was easily eroded. Such successive events that occur within less than a day are not uncommon in winter for the Palouse region. Therefore, it is important to include the dynamic soil properties, in particular the soil strength parameters, in process-based erosion models.

WEPP Simulation Results

Runoff and erosion results from the four WEPP runs, together with the field observations, are shown in Table 3. Comparison of WEPP-predicted (from Run 4) and field-observed runoff and erosion events is also shown in Fig. 6. When the original WEPP code is used, the reduction of saturated hydraulic conductivity under

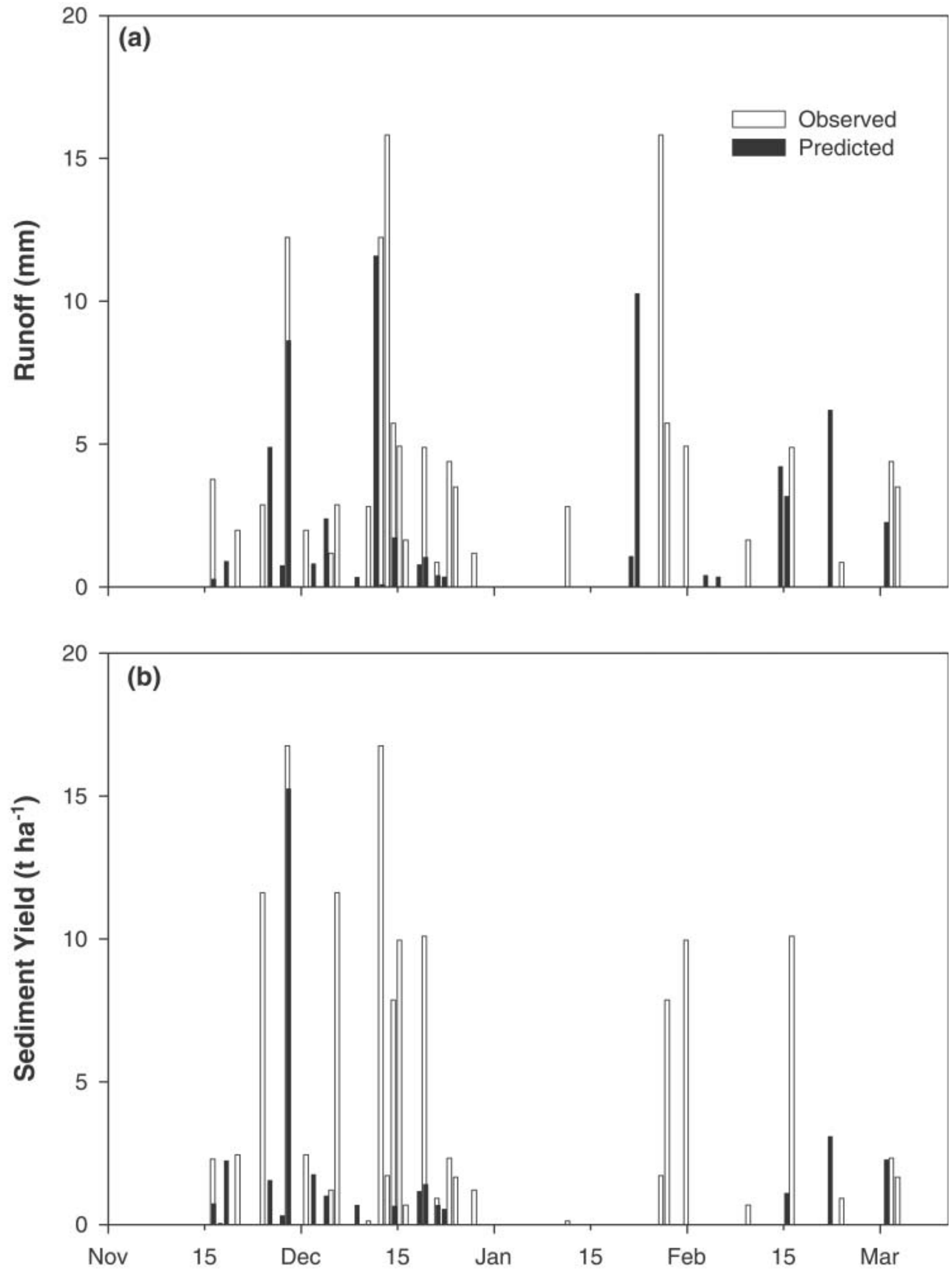

Fig. 6. (a) Observed and (b) WEPP-predicted runoff and erosion for Plot 1 under conventional tillage.

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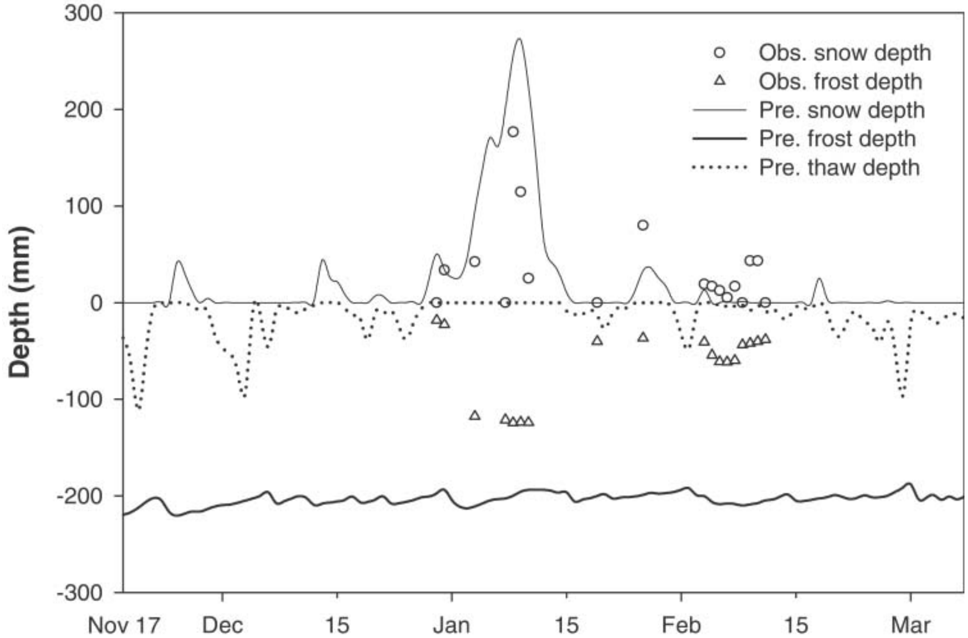

Fig. 7. Comparison of field-observed and WEPP-predicted snow, frost, and thaw depths. No event-based thawing depths were recorded during the field experimentation. Note that frost tubes were not installed until late December.

normal conditions, K, by a maximum of 10 times during freezing events would lead to K values still greater than average rainfall intensity in most cases, resulting in only one runoff event. By reducing K by 10 000 times, the discrepancy between the observed and predicted total runoff, for the winter season, was dramatically reduced. If the K was reduced by 20 000 times, the observed and predicted runoff were highly agreeable. It should be noted that, the lab-measured K value of 3.94×10^{-5} m s^{-1} in this study was higher than those reported in several previous studies (e.g., Fuentes et al., 2004; Kenny, 1990; Elliot et al., 1989). A lower K value would have required a lesser adjustment of this value in the winter routine. Additionally, a high K value may have contributed to the underestimation of surface runoff and erosion under the "non-winter" mode. WEPP predicted a total of 26 events compared with 14 events observed. WEPP defines an event on a daily basis, whereas an observed event may span more than 1 d; still, the occurrence of runoff events by WEPP was probably an overprediction.

In principle, water erosion is largely driven by runoff. In the first simulation, neither runoff nor erosion was predicted. In the second and third runs, the predicted runoff was increasingly closer to field observation. However, erosion was substantially underpredicted. By reducing τ_c to a rather low value of 0.1 N m^{-2}, the predicted (34.6 t ha^{-1}) was roughly one-half of the observed value (69.7 t ha^{-1}). This result may suggest that, for unconsolidated soil, which had undergone freezing and thawing processes, the critical shear stress may have been substantially reduced. However, Van Klaveren and McCool (1998) did not observe such dramatic reduction in critical shear stress for the Palouse silt loam soil after the soil was completely thawed. Further research is needed to confirm the reduction of τ_c during the freezing and thawing process for highly erodible soils. On the other hand, both the rill and interrill erodibility appeared to change dynamically during the freeze–thaw processes. Hence, by increasing the values of these parameters, WEPP prediction and field observation may become more agreeable.

Figure 7 shows the comparison of field-measured and WEPP-predicted snow, frost, and thaw depths. Frost tubes were not installed until late December of 2003. For the period of January through March 2004, predicted and observed snow depths were agreeable. However, WEPP overpredicted frost depth and the duration. The thawing pattern appeared reasonable according to the measured soil temperature profile for Plot 1 (Fig. 2). The process-based winter hydrology routine of WEPP is designed to simulate snow accumulation and density, snowmelt, and soil frost and thaw, all on a hourly basis (Savabi et al., 1995). In the routine soil frost is affected by several major factors, including soil and surface conditions, tillage and residue management practices, duration and extent of freezing temperature, and the snow cover (Savabi et al., 1995). Given that the snow depth was reasonably simulated and that the surface and soil conditions, as well as the tillage operations, were reasonably well defined, it appears that the heat transfer processes within the soil profile need improvement.

CONCLUSIONS

The unique winter climatic conditions, steep topography, and winter wheat cropping with conventional tillage combine to create large winter runoff and erosion events in the Palouse area of the Northwestern Wheat and Range Region. This study focused on detailed field monitoring and modeling of runoff and erosion events from two different management practices at the PCFS near Pullman, WA, during the 2003–2004 winter season.

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In addition to surface runoff and erosion, soil water and temperature profiles were continuously monitored to provide information on soil moisture and temperature conditions under which runoff and erosion occurred. In general, the no-till plots generated little to no runoff and no erosion throughout the season. The conventionally tilled plots, however, all produced considerably higher runoff and erosion exceeding the NRCS recommended tolerable rate. Differences in runoff and erosion existed among the three CT plots, possibly reflecting the lingering influence from a previous study and the naturally occurring spatial variation.

Two main mechanisms causing runoff and erosion were observed in the field. First, runoff and erosion may result solely from soil thawing and snowmelt. Without any precipitation input, the presence of frozen soil layers could prevent infiltration of snowmelt, causing saturation-excess runoff and erosion. Second, when rain fell on a snow-covered frozen ground, runoff would start as a consequence of the rain input and snowmelt. Higher rate erosion was evident when the additional rainfall caused substantial increase in soil moisture and lowered soil erosion resistence. Such successive events may not happen frequently but are very dynamic and can generate considerable amounts of sediment from uncovered surfaces.

The USDA's WEPP model contains a physically based winter routine to simulate snow cover and soil frost and thaw. Although WEPP could reasonably reproduce certain winter processes (snow and thaw depths) after code modification and parameter adjustment, it is not yet able to represent all the complex processes of winter erosion, as observed in the inland PNW. Improved knowledge of heat and water migration during the freezing–thawing processes is needed to better quantify soil strength changes, and thus soil erosion, in the winter season. Future efforts should focus on laboratory and field investigation of the dynamic winter runoff and erosion, so that these processes can be properly represented by a physically based erosion model.

ACKNOWLEDGMENTS

This research was supported in part by the USDA-CSREES-NRI Watershed Processes and Water Resources Grant 2002-01195. We thank John Morse, Hanxue Qiu, Toby Greer, and Li Wang for their help with the field runoff and erosion experimentation, and Travis Parry and Colette Easter for their help with soil sample analysis. We also thank Shuhui Dun for her assistance in modifying and running the WEPP model, and Randy Leek for his comments and suggestions to refine the manuscript. We are grateful to Dr. William Elliot, another anonymous reviewer, and Drs. Dennis Corwin and Jan Hopmans, Associate Editors of VZJ, for their valuable comments and suggestions in improving the manuscript.

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